JWST Point Spread Function Quality and Stability: Ground Testing, Integrated Modeling, and Space Validation

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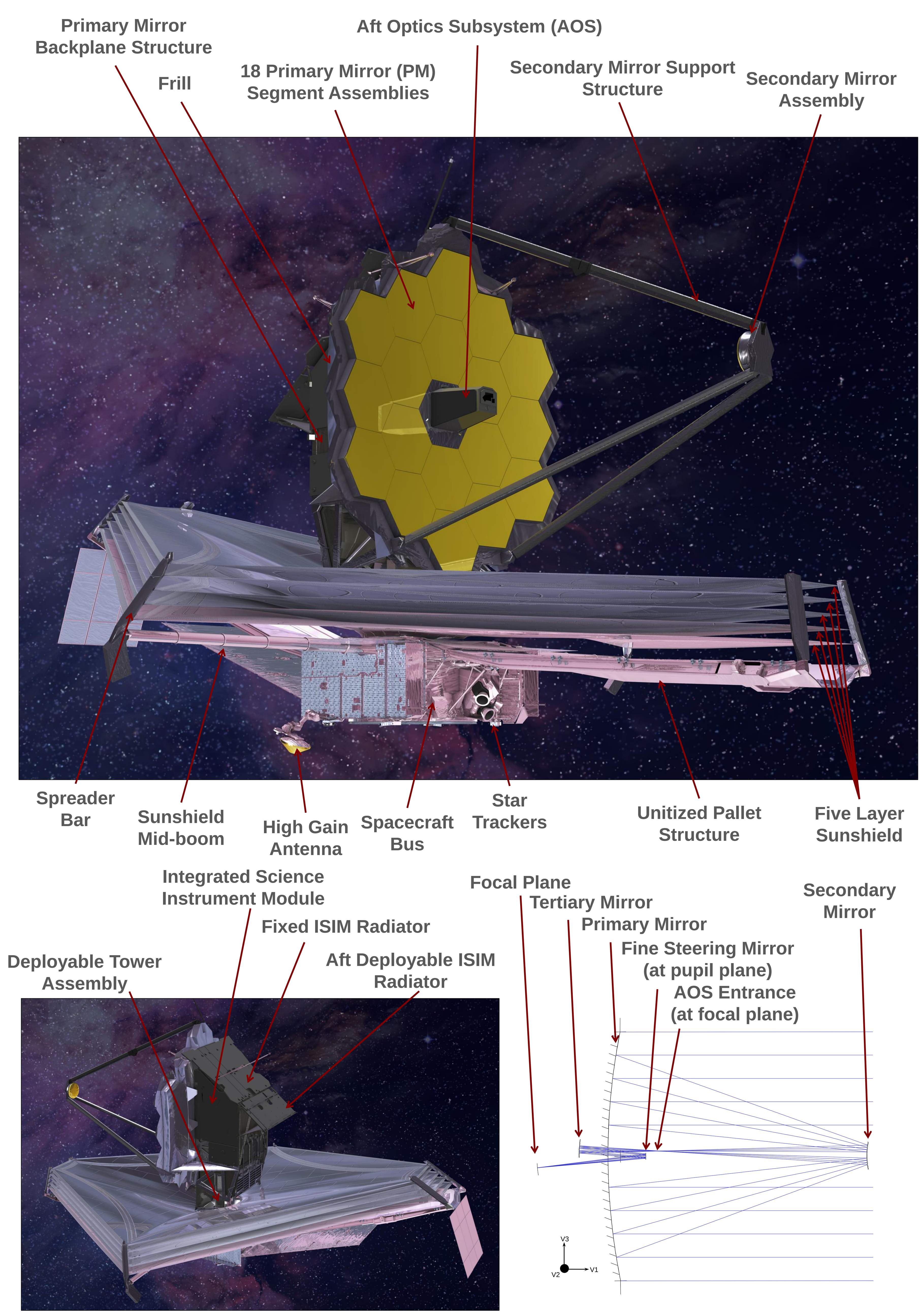
Abstract

The James Webb Space Telescope (JWST) is a large (6.5 m) cryogenic segmented aperture telescope with science instruments that cover the near- and mid-infrared from 0.6-27 microns. The large aperture not only provides high photometric sensitivity, but it also enables high angular resolution across the bandpass, with a diffraction limited point spread function (PSF) at wavelengths longer than 2 microns. The JWST PSF quality and stability are intimately tied to the science capabilities as it is convolved with the astrophysical scene. However, the PSF evolves at a variety of timescales based on telescope jitter and thermal distortion as the observatory attitude is varied. We present the image quality and stability requirements, recent predictions from integrated modeling, measurements made during ground-based testing, and performance characterization activities that will be carried out as part of the commissioning process.

JWST Observatory Overview



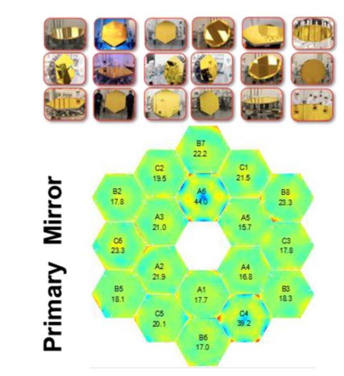
Top, Bottom Left: James Webb Space Telescope in its deployed state for science operations. The integration activities are separated into the telescope and science instruments (OTIS), sunshield, and spacecraft. After testing at the sub-system level, these elements will be integrated together at Northrop and tested again at the Observatory level before launch. **Bottom Right:** Ray-trace diagram for the JWST Optical Telescope Element.

Image Quality and Stability

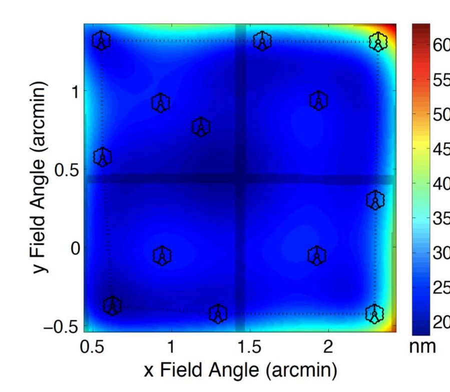
The JWST image quality and stability requirements were defined for the end to end Observatory optical system, from the primary mirror segments to the science instrument focal planes. The optical system must meet these requirements with both the static and dynamic errors. The image quality requirement was expressed as being diffraction limited or as having a strehl ratio (SR) greater than or equal to 0.8 at 2 μm in NIRCam and 5.6 μm in MIRI. The stability requirements were separated into a short term, 24 hour, encircled energy (EE) variation of less than 2.3% RMS about the mean EE and a 14 day EE variation of less than 3.0% about the mean following a worst case cold to hot slew. These requirements are verified by a combination of ground tests and integrated modeling analysis. The Observatory performance will be validated during commissioning.

Ground Testing

The image quality requirements are verified during a series of tests at the major stages of integration. component level (e.g., mirrors), the subsystem level (e.g., Science Instrument (SI), Integrated Science Instrument Module (ISIM)), and the OTIS level.

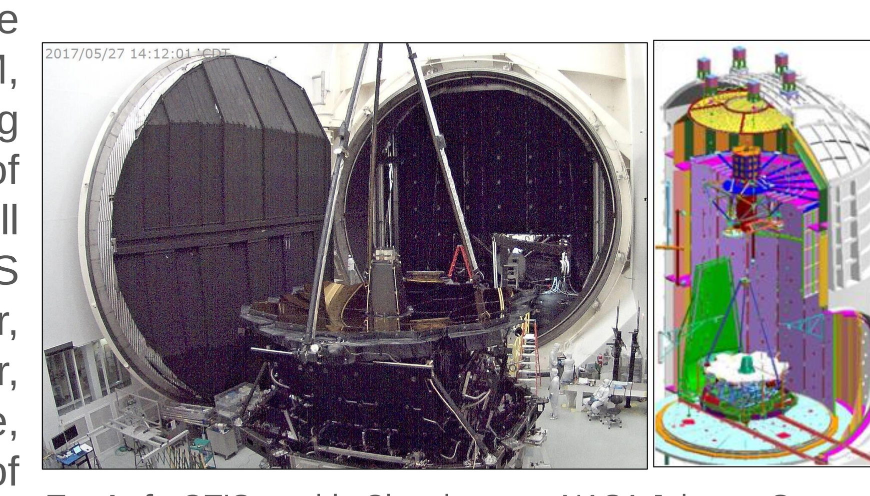


Component Level Testing: Each of the telescope mirrors have been evaluated at the component level and are within their requirements. The residual rms wavefront was measured at the cryogenic temperatures, The primary, secondary, tertiary, and fine steering mirror, the four mirrors that comprise the telescope, are all within requirements. **Right:** The as-built primary mirror wavefront map (Lightsey et al. 2014).



ISIM level testing: The SI requirements at the ISIM level were verified in the second (CV2) and third (CV3) ISIM cryovacuum tests. These cryo-tests were carried out before and after vibration exposure to ensure the optical performance was maintained. Between these tests, there were several hardware modifications including shimming detector, replacing detectors, and replacing a microshutter array **Left:** For example, the NIRCam A wavefront error map across the field of view (Aronstein et al., 2015).

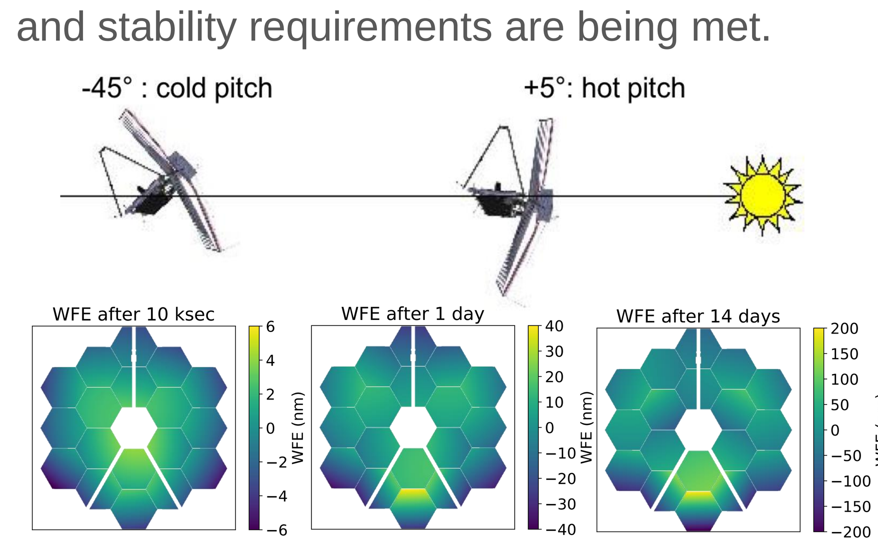
OTIS level testing: Cryovaccum testing at the OTIS, the Optical Telescope Element + ISIM, level. At right is the OTIS cryo-testing configuration, scheduled to begin at the end of this month and run for 93 days. This test will measure PM to AOS alignment, SM to AOS alignment, AOS to ISIM despace/decenter, NIRCam aperture stop to FSM mask decenter, ISIM tilt via entrance pupil and object surface, ISIM object surface clocking, PM radius of curvature, PM to FSM alignment, WF control capability, a series of crosschecks, PM thermal distortion model validation, and a platescale calibration.



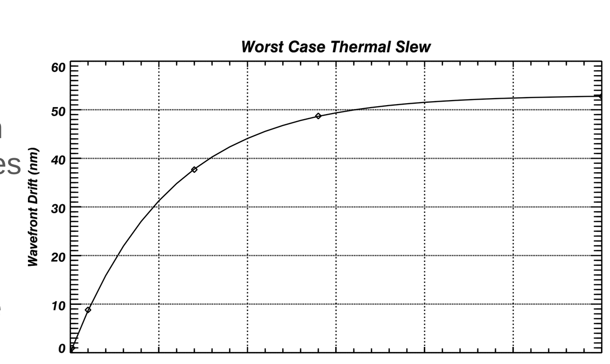
Top Left: OTIS outside Chamber at at NASA Johnson Space Center in preparation for the cryo-optical testing (May 2017, JWST Webbcam). **Top Right:** OTIS configuration for cryo-testing.

Integrated Modeling

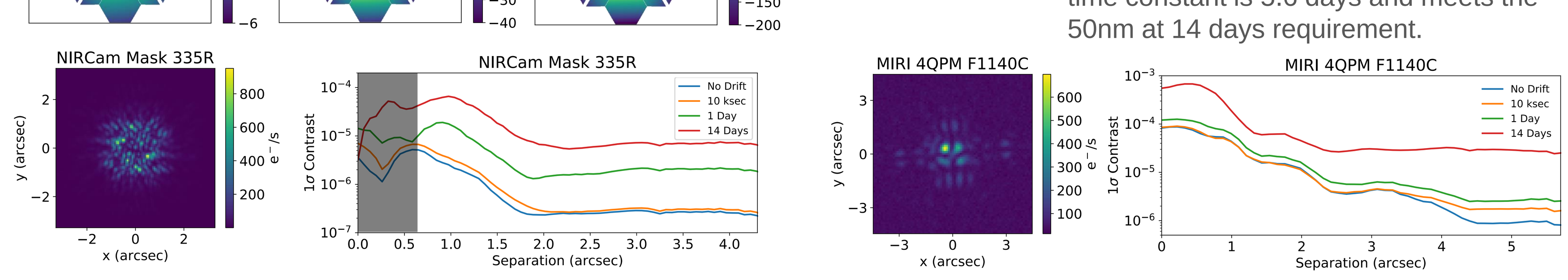
Expected telescope stability and image quality performance have been simulated with end-to-end modeling. A software package called the Integrated Telescope Model (ITM) generates PSFs based on existing ground test data (where possible) and integrated modeling analysis for thermal distortion (TD), deployed dynamics, and pointing control. Monte Carlo simulations of the commissioning process have been used to evaluate the distribution of optical realizations based on the expectations from test and analysis. These optical alignments are subject to thermal distortion as the Observatory is pointed from one attitude to another. The optical stability is based on structural, thermal, and optical performance (STOP) integrated models. From the structural deformations, optical path difference maps are produced, which are then used to generate the wavefront drift and assess time constants and total wavefront drifts. In addition, the telescope pointing is expected to roll about the fine guidance sensor as the star trackers change thermal states. The integrated modeling shows that the image quality and stability requirements are being met.



Left Top: Schematic of pitch change that creates worst case TD. **Left Bottom:** Integrated modeling estimate of the TD induced WFE map following a hot to cold thermal slew.



Top: Integrated modeling prediction for TD from a worst case thermal slew. The time constant is 5.6 days and meets the 50nm at 14 days requirement.



Coronagraphy: As the telescope changes thermal states, optical distortion reduces the coronagraphic performance. Target PSFs were generated using the baseline optical alignment, including the expected levels of jitter, target acquisition error, and detector effects. From this baseline, the worst case wavefront drift was added to create a reference PSF and then pairwise subtracted from the target PSF. A covariance matrix was computed to assess the noise properties, which includes speckle, detector, and photon noise. The azimuthal mean of the noise was normalized by the value of the unocculted source to produce the 1σ contrast. **Top**: NIRCam 335R and MIRI 4QPM PSFs and contrast curves.

Space Validation

Image Quality: The initial telescope alignment will be completed with a series of activities that make use of specialized NIRCam modes for wavefront sensing. The telescope jitter will be measured before the cryocooler is turned on. After the telescope is aligned at several field points within NIRCam, the image quality will be assessed at multi-instrument multi-field (MIMF) points. **Image Stability**: The image stability requirements will be validated during commissioning. After the telescope is aligned, routine wavefront monitoring will take place every 2 days with corrections to the telescope no more than every 14 days. The drift and time constants of two conditions will be evaluated using a hot to cold thermal slew activity following the telescope alignment.

References

Aronstein, D. L., Smith J. S., Zielinski, T. P., et al., 2016, Proc. of the SPIE, 9904, 990409
Lightsey, P. A., Knight, J. S., & Golnik, G., 2014, Proc. of the SPIE, 9143, 914304